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13. ABSTRACT (Maximum 200 words)

This report details the scientific progress and accomplishments of the work carried out during the time period of grant number DAAD19-99-1-0033 (3/1/99 - 2/28/01). The goal of this project was to produce high contrast atomic gratings with a period that is an integer fraction of an optical wavelength. Research was carried out with both a magneto-optical trap (MOT) and an atomic beam. Progress was made in (i) the use of optical masks to create high contrast atomic gratings and gratings with a period that is a fraction of an optical wavelegth in a MOT, (2) optimization of an atomic Rb beam, and (3) one dimensional transverse laser cooling of the atomic beam.

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I. PUBLICATIONS

(c) Papers Presented at meetings

A. Turlapov, D. V. Strekalov, A. Kumarakrishnan, S. B. Cahn, and T. Sleator, *Sub-optical wavelength atomic gratings generated in a time-domain interferometer*, Centennial Meeting of the American Physical Society, March 20-26, 1999, Atlanta, Georgia, Bull. Am. Phys. Soc. **44**, 1644 (1999).

D. Strekalov, A. Turlapov, A. Kumarakrishnan, S. Cahn, and T. Sleator, *Phase Space Imaging of Trapped Atoms Using Magnetic Sublevels Coherence, ibid.* **44**, 1154 (1999).

A. Turlapov, D. V. Strekalov, A. Kumarakrishnan, S. B. Cahn, and T. Sleator, *Periodic atomic structures fabricated in a time-domain interferometer*, Int. Conf. Atom Optics Applications, 23 - 28 May 1999, Les Houches, France.

A. Turlapov, A. Tonyushkin, and T. Sleator, *Optical mask for laser cooled atoms*, 2001 Annual Meeting of the Division of the Atomic, Molecular, and Optical Physics of the American Physical Society, May 2001, London, Ontario, Canada (DAMOP'2001).

T. Sleator, *Creation and detection of sub-optical wavelength atomic density gratings using laser fields*, 3rd Annual Cross Border Workshop on Laser Science, May 23-25, 2001, Toronto, Canada (invited talk).

II. PARTICIPATING SCIENTIFIC PERSONNEL

Prof. T. Sleator (Principal Investigator)
Andrey Turlapov (Graduate Student)
Alexei Tonyushkin (Graduate Student)

III. REPORT OF INVENTIONS

None.

IV. SCIENTIFIC PROGRESS AND ACCOMPLISHMENTS

The equipment supported by this grant was used to facilitate and extend the research projects funded by the ARO entitled "Atomic Interference in Standing Wave Fields", grant number DAAG55-97-1-0113, and "Atomic Manipulation Using Optical Fields", DAAD 19-001-0412. These projects are a collaboration between Professor Sleator's group at NYU Professor Paul R. berman's group at the University of Michigan, which is providing theoretical support.

The long-term goal of these projects is to create nanostructures by passing a beam of atoms through two or more standing wave light fields. Following interaction with the standing wave fields, the atomic density contains all even spatial harmonics of the standing wave light field. At appropriate distances following the interaction with the light fields the different harmonics are focused, enabling one to isolate each of the harmonics. By transferring the atomic density spatial distribution to a surface, one can create pure harmonic gratings having periods as small as tens of nanometers. In addition to forming pure harmonic gratings, we are working on methods to effectively focus atoms with high periodicity (of order 50 nm). Methods for probing the density patterns with nanometer resolution are also being explored. The research effort is a combined theoretical-experimental program, with the theory component housed at the University of Michigan and the experimental component at New York University.

This report covers the work carried out at NYU during the period 3/1/99-2/28/01. Progress has been made in (i) optical masks, (ii) optimization of the atomic Rb beam, and (ii) one dimensional transverse cooling of the atomic beam.

A. Optical mask

We have carried out experiments on laser cooled Rb atoms to test an *optical mask* scheme for both production and detection of periodic atomic density distributions. An optical mask would allow us to directly measure an arbitrary atomic density distribution of period $\lambda/2$ with a resolution much less than an optical wavelength, as well as to create atomic density distributions of period $\lambda/2$ with very sharp features and with periodicities an (even) integer fraction of an optical wavelength. Our optical mask experiments consist of two parts, creation of atomic structures, and measurement of the atomic density resulting from these structures.

1 concept of the optical mask

To use an optical mask to create atomic structures, a standing wave pulse was applied to the cold atoms, as shown in Fig. 1. The frequency of this pulse was made resonant with the F = 3 to F′ = 3 transition ($5S_{1/2}$ to $5P_{3/2}$). The excited F′ = 3 hyperfine state can decay to the F = 2 ground hyperfine state (as well as the F = 3 ground state) allowing a net loss of atoms from the initial F = 3 ground state hyperfine level. This pulse can be thought of as producing an atomic periodic structure, in that all atoms *not* at the nodes of the standing wave will be pumped into the F=2 hyperfine level, and effectively lost. After the pulse has terminated, the atoms remaining in the F=3 state are localized at the nodes of the field. The degree of localization depends on the properties of the field, such as the peak intensity and pulse duration, and under appropriate conditions can be a small fraction of an optical wavelength.

To detect the resulting periodic structure we applied a "detection sequence", consisting of an optical standing wave, identical to the one described above (tuned to the F=3 to F′ = 3 transition), followed by traveling wave tuned to the F=3 to F′ = 4 transition, which is a closed transition (See Fig. 2). The fluorescence from the atomic cloud during the traveling wave pulse was recorded. The fluorescence signal is proportional to the number of atoms that "survive" the standing wave pulse, or equivalently, the number of atoms in the vicinity of the nodes of the standing wave. Repeating this sequence of pulses while scanning the nodes of the standing wave over one period (half a wavelength) allows one to map out the atomic density as a function of position. The measurement resolution is determined by the intensity and duration of the standing wave pulse.

2 Creation and detection of sharp features of period $\lambda/2$

In an initial experiment we applied a creation sequence, immediately followed by a detection sequence. In this situation, one would expect to see a fluorescence signal only when the nodes of the two standing wave are aligned. The experimental setup is shown in Fig. 3. The standing wave for this experiment was generated by two traveling waves at a small angle (1.5°), resulting in an effective wavelength "λ" much larger than the wavelength of the laser fields. This large wavelength was used in these initial experiments to allow longer interaction times with the optical mask pulses. (Due to the thermal velocity spread of the atoms in the cloud, any periodic structure produced will eventually become washed out, as discussed below. The smaller the structure, the more quickly it becomes washed out.) Fig. 4 indicates that the structures produced are a small fraction ("λ"/18) of the effective wavelength. If we assume that the instrumental resolution in the measuring phase of the experiment is roughly equal to the size of the structures produced, then we may conclude that the structures produced are about 1/25 of the effective wavelength. The small size of the structures relative to the wavelength indicates that this technique may have much promise for producing periodic nano-structures.

3 Creation and detection of structures of period $\lambda/2N$ using "echo" techniques.

If one increases the time between creation and detection of the atomic gratings, one finds the the grating will be washed out over a period of time inversely proportional to the velocity spread of the atoms (the characteristic time is the time a typical atom takes to travel a distance equal to the grating period). Even though the grating is washed out, there is still a correlation between the position and velocity of the atoms. Applying a second mask at some time T after the first mask will cause atomic gratings to reform at various times after the second mask (see Fig. 5). At $2T$ one will find a grating with the same period of the standing wave forms. More interestingly, at time $(3/2)T$ one will find a grating of period *half* the period of the original grating. At $(4/3)T$ a grating will form with period 1/3 the original grating. One can understand this as a simple "shadow" effect.

We have made some preliminary measurements of the production of higher order gratings using the shadow effect. Figure 6 shows the results of an experiment consisting of two standing wave pulses separated by time T followed by
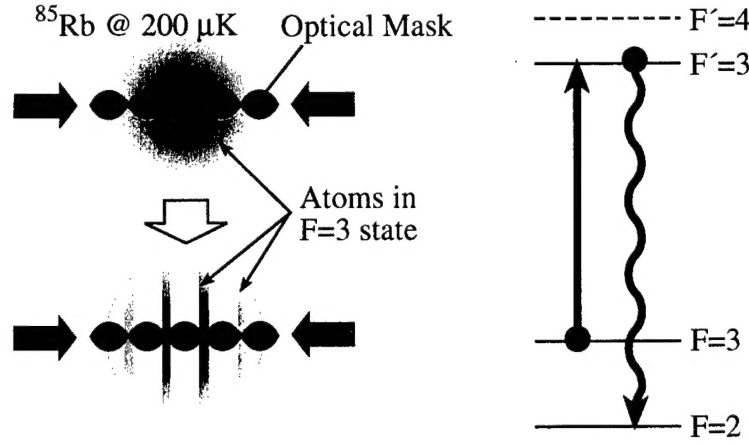
FIG. 1: Scheme for producing a periodic atomic structure with an optical mask: a) shows the effect of the standing wave pulse on cold cloud of Rb atoms. b) shows the mechanism by which all atoms except those at the nodes of the standing wave are pumped into the F=2 ground state hyperfine level. The straight line represents the absorption of a laser photon, and the wavy line represents the spontaneous emission of a photon.
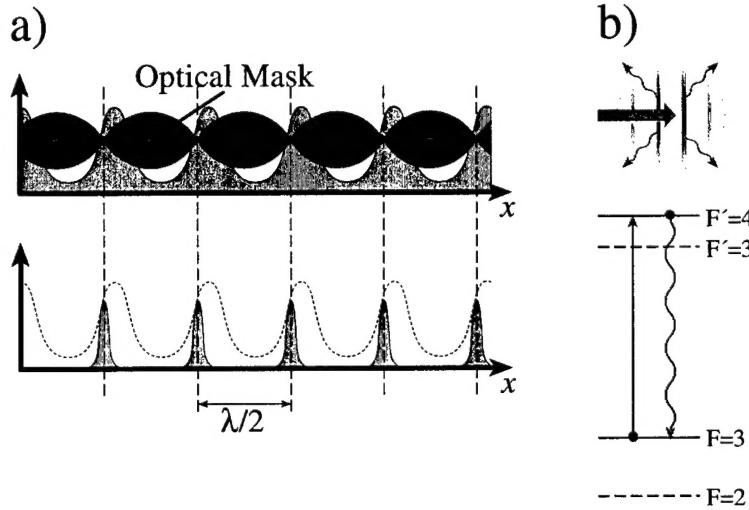

FIG. 2: Scheme for measuring a periodic atomic structure with an optical mask: a) shows the effect of the standing wave pulse on an initial periodic distribution of atoms in the F=3 state. The light shaded region shows the density of atoms in the F=3 hyperfine state before (upper curve) and after (lower curve) the standing wave pulse. b) shows the scheme by which the number of atoms remaining in the F=3 state are measured. The wavy line in the level diagram correspond to the fluorescent photons that are measured in the experiment.

a measurement sequence at time $(3/2)T$. Data have also been taken for $t = (4/3)T$ revealing a grating of period $\lambda/6$ (or 1/3 the standing wave period).

We are currently working to improve the resolution of our higher order gratings. Our next step will be to repeat the experiments with counter-propagating traveling waves to reduce the size of the structures.

B. Beam optimization

An atomic beam apparatus was constructed using a recirculating oven as a source of Rb atoms. The properties of the beam were characterized from measurements of the absorption from a weak frequency scanned laser beam. Typical parameters are a beam velocity of about 500 m/s, with a longitudinal spread of about 40% (full width at half max). Typical densities were about 10^8 atoms/cm^3 at 1 meter from the source, and atomic fluxes of about 5×10^{12} atoms/second.
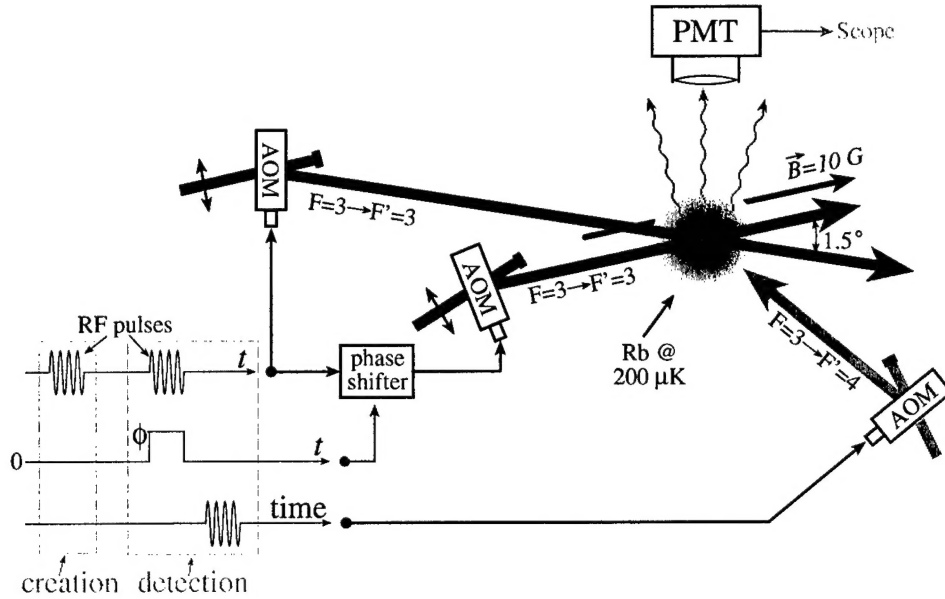
FIG. 3: Experimental setup for the optical mask experiments. All laser fields are switched on and off by acousto-optic modulators (AOM). The lower left of the figure shows the timing of the rf pulses used to switch on the laser fields. The phase shifter is used to shift the nodes of the standing wave during the detection phase of the experiment.
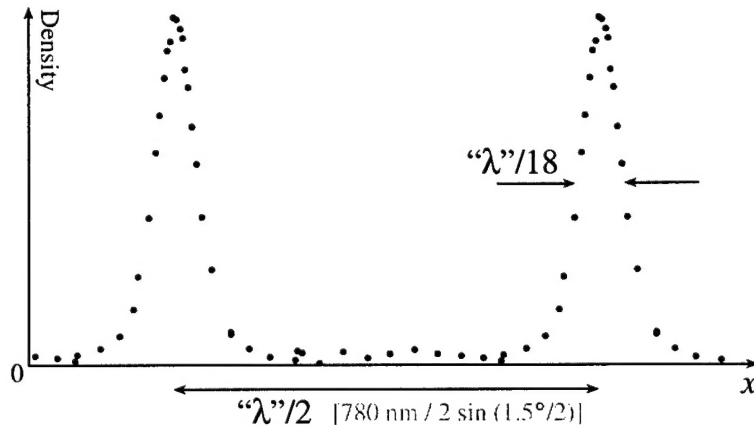

FIG. 4: Results of the optical mask experiment: Fluorescence signal as a function of the shift in the nodes of the second standing wave relative to the first.

C. One dimensional transverse cooling in the atomic beam

Experiments have been carried out on one dimensional transverse cooling of the atomic beam. The degree of cooling was determined by time-of-flight measurements of the velocity distribution. These measurements were made by imaging the fluorescence from the atomic beam downstream from the cooling region to get the size of the beam. The results of these experiments indicate that significant cooling is taking place. Although a smaller transverse velocity spread should result in a *magnetic grating free induction decay* (MGFID) signal of longer duration, no such effect was observed. We are currently trying to understand the relationship between the time-of-flight cooling results, and the lack of the effect of cooling on the MGFID signal.

Resolution of these problems will allow us to proceed to the next step of producing atomic density gratings in the atomic beam by the application of optical standing waves.
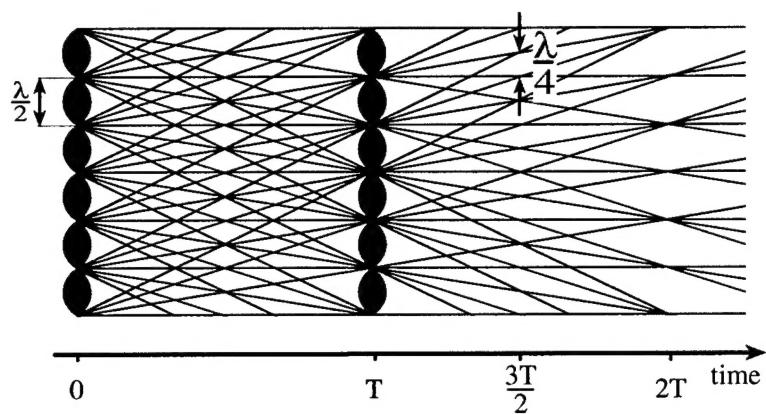
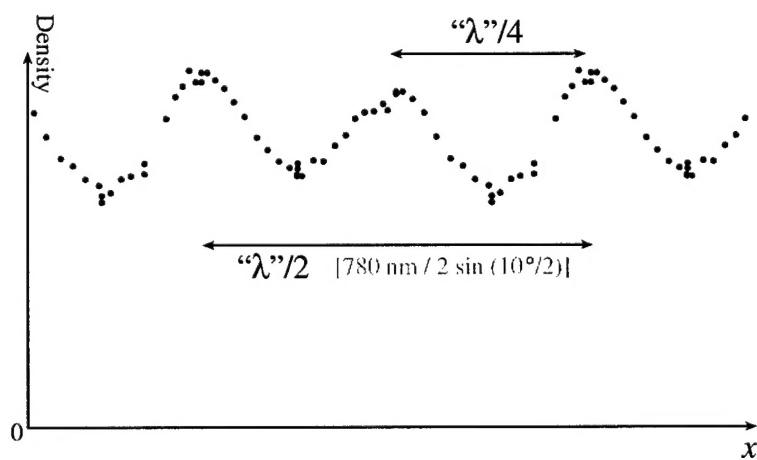FIG. 5: production of higher order gratings using the shadow effect

FIG. 6: experimental results for the production of higher order gratings using the shadow effect